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International Journal of Industrial Ergonomics 26 (2000) 163–176

International Journal of
Industrial
Ergonomics

www.elsevier.nl/locate/ergon

Relative advantage of portable computer-based workcards for aircraft inspection

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Abstract

Following a successful demonstration of the applicability of human factors guidelines to the design of aircraft maintenance documentation (Patel et al., 1994, Applied Ergonomics, 25 (5) 286 – 293) a natural extension was to replace paper-based workcards with a computer system. Using additional human factors guidelines for design of computer systems, a prototype hypertext system was developed for use on a portable computer. A number of different workcards were accommodated, and an evaluation made of the computer-based workcard against both original and improved paper-based workcards. For the task studied, eight inspectors rated the computer-based system highly on scales derived from the guidelines. The computer-based system was a significant improvement over the original paper-based workcards.

Relevance to industry

Process documentation and work instructions need to be used in many industries, particularly those certified under the ISO-9000 series of standards. An obvious way to improve the management of documentation is to deliver it to the user electronically. This paper shows how the user interface to such a system can be designed. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

The work control card, or workcard, is the primary job aid for aircraft maintenance and inspection. It provides specific instructions on the task(s) to be accomplished, with directive information such as which defects to inspect for, warnings about aircraft and personal safety and details of tools and equipment needed. In addition it provides specific places where the aircraft maintenance technician (AMT) or inspector must sign off a task step as having been successfully accomplished. Such a listing is called an Accountability List. Finally, for inspection tasks, any discrepancies or defects discovered generate Non-Routine Repair (NRR) reports which in turn generate new workcards for their completion. Because of their importance to safe aviation, the design of workcards for error-free task performance is a major task of the manufacturers and airlines.

A broad study of human factors in aircraft maintenance and inspection (Drury and Lock, 1994)

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PII: S0169-8141(99)00064-5

found that workcard design did not conform to existing human factors guidelines for information design. Earlier, Bohr (1978) had found similar problems with operating procedures, manuals and checklists in nuclear power plants in Germany. Because of this, a comprehensive design exercise was undertaken by Patel et al. (1994), resulting in a set of guidelines, example workcards generated from these guidelines, and a direct evaluation of original and redesigned workcards using scales derived from the guidelines. At the end of the Patel et al. (1994) paper, it was noted that

> all of the design principles developed here apply equally well to portable computer-based documentation systems.

The current paper transfers the improved design to a portable computer and tests the result against both the original and improved paper-based workcards. Two objectives were important in the evaluation:

1. to determine whether the computer-based system was an improvement over paper-based documentation,
2. to examine the relative contributions of computerization and the use of the generic guidelines developed earlier.

Portable computer-based workcards can overcome some limitations of paper-based workcards. Feedforward and feedback information can be presented, in addition to traditional directive information (Prabhu and Drury, 1994). An example of feedforward information would be telling the inspector of previous defects found in other aircraft. Feedback information can come from comparing a response (e.g. a recorded part serial number) with a list of possible values, and flagging responses which are not on the list. Access to detailed information in attachments and maintenance manuals is easier. The display can act as an external working memory keeping all relevant information in front of the user at all times. Computer-based information also provides additional flexibility for organizing information about the tasks. Multi-layered information usage can cater to the needs of both experts and novices. As an example of these benefits, Glushko (1989) described the advantages of using an "intelligent electronic manual" in organizing the information contained in maintenance manuals. According to Higgins (1989), there can be as many as 70 manuals for one aircraft type, with literally millions of pages of documentation.

Advances in portable computing systems make it more feasible to realize these benefits. The combination of inspectors' increasing information needs and technological advances ensures that portable computer-based workcards will eventually replace traditional hardcopy workcards. Specialized computer hardware and software systems have been designed to automate complex diagnostic tasks (maintenance) such as the Air Force's Integrated Maintenance Information System (IMIS) (Johnson, 1989). There remains a need for a simpler, less-expensive system using off-the-shelf components. Prior computer-based systems such as IMIS have been aimed at diagnostic tasks where they can support rule-based reasoning, but here they were applied to the more information-intensive procedural tasks that form a major portion of aircraft inspection activity. The objective of this study was to develop and test a prototype of a simple, inexpensive inspection workcard implementation on a lap-top computer. Specifically, the design had to be effective for both the repetitive, less detailed A-checks and the less-frequently-repeated and more complex C-checks performed by inspectors on typical airliners. Positive findings in the aircraft maintenance domain could give encouragement to developers of computer-based systems for other domains, such as process plant maintenance.

The computer-based workcard's design used and extended the guidelines developed for the paper-based workcard. Computerization of information solves some problems, but opens a new set of problems that this project had to identify and resolve. The computer-based workcard's design was evaluated against the paper-based workcard's to determine if these issues were properly identified and resolved.

2. Computer-based workcard development guideline development

For this study, much of the information developed by Patel et al. (1994) could be utilized. For example, at the airline used in the study the same

original workcards were still being used with no large-scale personnel changes so that the field visits, task analyses (Drury et al., 1990), observations, and questionnaire responses were still valid. In summary, these prior observations showed dissatisfaction with many aspects of the current workcard, particularly in its sequencing of activities and integration with secondary information such as graphic attachments from various sources (e.g. manuals, directives). Two contrasting types of inspection procedures were studied. The A-checks were typically long sequences of often-repeated short tasks, where sequence and convenience were most important. In C-checks, where an inspector may only encounter a typical task at intervals of several weeks, the issues mainly concerned layering of information to support reduced levels of familiarity with task specifics.

Similarly the document design guidelines developed in the earlier study still applied. There were 49 guidelines categorized under:

1. Information Readability (8 guidelines),
2. Information Content (25 guidelines),
3. Information Organization (9 guidelines),
4. Physical Handling Environment (7 guidelines).

However, introduction of computer technology required additional guidelines to ensure accordance with published human factors principles. While there are many sources of such design information, the guidelines developed here, shown in Table 1, were largely from Brown (1988) and Smith and Mosier (1986). More recent guidelines, e.g. Mayhew (1992) have added new technology to graphical user interface design, but have not invalidated the principles presented in Table 1. A comprehensive set of guidelines are contained in Marcus (1997). The structure of our guidelines has been designed to conform as closely as possible with the paper-based guidelines, as can be seen from the major headings in Table 1.

3. Hardware issues

The choice of hardware for the computer-based workcard was a critical issue. The original

Table 1
Design guidelines for the computer-based workcard system

1. *Information readability*	
(a) Layout	1. Use a fixed set of proportions/grids
	2. Use spatial layout as a primary cue for object grouping
	3. Use a consistent layout across fields
	4. Use fixed size/location for "functional category fields"
	5. Left justify the most important information
	6. Use blank lines in place of graphic lines to reduce clutter
(b) Typography	1. Use upper case only for short captions, labels, and headings
	2. Use conventional punctuation and formalisms
(c) Metaphors	1. Be very explicit in the use of metaphors
	2. Use explicit screen transitions, e.g. iris open vs. scroll
	3. Use paper form metaphor for data input
	4. Use soft button metaphor for all external links
(d) Contrast	1. Use contrast sparingly and as a last option
	2. Use contrast to attract attention to select portions of text
	3. Use a maximum of three levels of contrast coding
2. *Information content*	
(a) Input information	1. Use familiar mnemonics for input
	2. Use congruent command pairs, e.g. R/Wrong, not R/Close
	3. Use "radio buttons" for all multiple choice information

Table 1 Continued
Design guidelines for the computer-based workcard system

(b) System output information	1. Use the display as an external working memory of the user 2. Provide screen identity information 3. Display only necessary information 4. Condense all unnecessary information into icons 5. Avoid a display density higher than 15% 6. Use the inheritance metaphor to identify position in hyperspace. 7. Use affirmative dialogue statements 8. Provide input acknowledgments and progress indicators 9. Use auditory feedback conservatively 10. System messages should be polite and instructive 11. Do not provide a system-initiated help feature
(c) Graphic information	1. Use graphics to reduce display density 2. Show all spatial, numeric, temporal information graphically
(d) Iconic information	1. Use icons for all direct manipulation 2. Use icons to save display space and reduce clutter 3. Use icons for all external links 4. Use icons to permit cross-cultural usage
3. *Information organization, manipulation, and access*	
1. Linking	1. Provide contextual internal links 2. Use internal links for all reference information 3. Use external links sparingly and only for non-contextual information. 4. Provide a link backtrack option 5. Provide an UNDO option for navigation 6. Make linking explicit; do not leave anything to exploration or browsing 7. Use linking sparingly to avoid user confusion and disorientation 8. Label links where possible
2. General organizational philosophy	1. Organize for progressive disclosure and graceful evolution 2. Keep layered information optional 3. Do not use scrolling fields 4. Organize tasks in a fixed linear as well as optional nested structures
4. *Other pragmatic issues*	
1. Physical handling and infield usability	1. Develop and implement standards for reverse video, contrast for varied lighting conditions 2. Follow a pencentric display design philosophy 3. Design for single-handed operation 4. Minimize the use of key entries, use direct manipulation
2. Hardcopy	Provide feasible options for obtaining hardcopies in a fixed format
3. System response time	Keep the system response times for all actions within standards
4. User acceptability	1. Honor user preferences 2. Provide only those functions that a user will use

paper-based system studied lacked a convenient hand-held integrated workcard holder, although one was designed for the improved paper-based system. The hand-held computing sector has seen some rapid advances. Mobile Data Acquisition (MDA) through hand-held computers has been greatly enhanced by the development of smaller data acquisition cards (Tristram, 1996). Hand-held

computers have been used for data collection in several industries including food processing, warehousing and industrial manufacturing sites (Richard, 1994). The moderate success of commercial products such as the Palm Pilot and Microsoft's hand-held PCs (products using the Windows CE operating system) indicates that the hand-held computer and its supporting technologies are becoming more robust and viable. Advances in handwriting recognition and speech recognition technologies (Markowitz, 1996) have made it possible to design mobile computers that are free of awkward pointer and keyboard interfaces. However, these new technologies have not yet been perfected, and can present designers and users with more problems than solutions. Some designers (Microsoft) have therefore opted to redesign the keyboard, and replace the mouse with a stylus and a touch screen. User testing of pen-based systems shows that user acceptance depends on the accuracy of the hand writing recognizer, but is also a function of the nature of the task being performed. Pen-based systems are considered to be viable for tasks that can be designed as highly structured tasks with screen prompts linked to clearly defined fields for text entry (Frankish et al., 1995). Aircraft maintenance workcards meet these specifications.

Designs of portable computers are getting more rugged, inspiring confidence when a computer is intended for field usage. The hardware chosen for this study had to be a laptop computer, as at the time of the study (1992–93) more advanced systems were not available off-the-shelf. Using laptop systems can still be inconvenient, due to keyboard and pointer interfaces. Systems operated by keyboards and mice partially defeat goals of accessibility and connectivity (Meyrowitz, 1991). Pen-based computing allows links between information to be created by a mere pointing gesture, but at the time of the study, this technology was still not reliable enough for field use without special support.

4. Software issues

As we have noted earlier, a key issue in information design for aircraft maintenance is layering, i.e. the support for different users to obtain different levels of detail of information. The mechanic who performs a procedure daily may be served by an overview of the necessary steps, e.g. a checklist, whereas a mechanic faced with a novel procedure may need more detailed information. In a computer-based system, this implies a form of hypertext. Hypertext is a technology of nonsequential writing and reading: it is also a technique, a data-structure, and a user interface (Berk and Devlin, 1991). Hypertext systems split documents into components or nodes connected by machine-supported links or relationships.

Hypertext features solve many design issues identified in the taxonomy developed by Patel et al. (1994). For example, computer-based information provides a consistent typographic layout and a continuous layout with no page breaks. It also reduces redundancy and repetition, fostering generalizations across tasks. Computer-based systems are more supportive of graphics than paper-based systems. Hypertext easily allows for categorization and classification of tasks and information so that general information can be separated from specific information. Layering of information is conducive to expert and to novice usage. Hypertext should make accessing and referring to information such as attachments and manuals considerably easier. In addition, the inspector can sign off tasks after completing them, write notes for nonroutine repairs in the computer-based system, and then easily return to the correct place in the task list to continue inspection.

Hypertext is not without its problems (Vora and Helander, 1997). Being able to link between nodes in a nonsequential manner may facilitate information layering, but it can also result in users losing track of their current position. Inspection and maintenance tasks are typically ordered, so that step (i) must be completed before step ($i + 1$) can begin, implying that care must be taken in designing the hypertext system to prevent loss of place information. In our workcard implementation, moving away from the strict sequential order (e.g. to recall back-up documentation) brought up a new overlaying window, which eventually had to be closed to continue the task. This is what Vora and Helander (1997, p. 881) call "chronological

backtracking". They claim that backtracking is the most important navigation facility in hypertext. In addition a sequential listing of all tasks completed, referred to as an Accountability List, was maintained by the software and could be called up at any time.

5. Final design

The next step is to design specific examples of computer-based workcards, using the lessons learned from designing paper-based workcards, knowledge of hypertext, and analyses of inspection tasks.

A prototype computer-based workcard system was developed on an IBM Think Pad 700 PS/2 using Spinnaker PLUS. This hypertext program is an object-oriented programming language that simplifies creation of detailed information management applications by using links between stacks of information. Eight different inspection tasks were implemented into the system. A-check inspection tasks for a B727-200 included logbooks, nose landing gear, main landing gear, aircraft wings, aircraft empennage, and aircraft fuselage inspection. Left wing and right wing inspection for a DC-9-30 C-check were also programmed.

System design adhered to the lessons learned from developing the paper-based workcard identified in Patel et al. (1994). The design also followed design guidelines specific for computer interfaces identified in Table 1.

The computer-based workcard met these design guidelines using the logic shown in Fig. 1. The first workcard screen is the input manager which the inspector/mechanic uses to enter data normally found at the top of every page; the inspector/mechanic name and identification number, the supervisor, and the aircraft's identification number. This information is then reproduced on all other documentation such as the Accountability List and the Non-Routine Repair forms, relieving the inspector of repetitive form filling. The global view (Fig. 2) displays all inspection tasks and highlights completed tasks, serving as an external display to augment working memory. While performing the tasks, the inspector/mechanic has direct access to

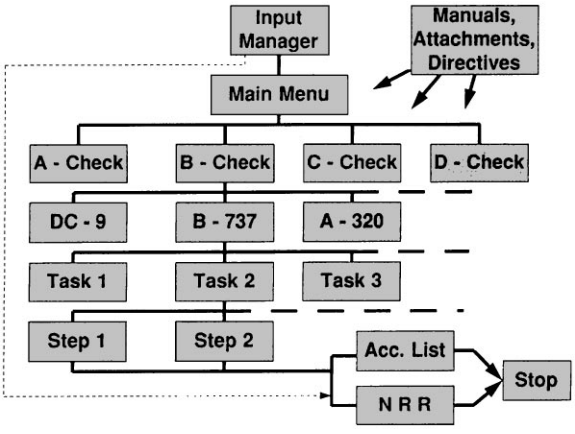

Fig. 1. Logic of hypertext computer programs.

both input and output information such as the general maintenance manual, the airplane's manufacturer maintenance manual, engineering change repair authorization(s), airworthiness directives, and attachments. This eliminates the need for the inspector/mechanic to carry bulky attachments or to leave the inspection site to refer to a manual. For each task, the inspector/mechanic has options of signing off, reporting a non-routine repair (the text icon), making a note on the writeup note feature, going to the home screen to show the signoffs remaining for the task (house icon), going to the global screen (globe icon), viewing an overview feature displaying the number of completed signoffs, or using a help feature (query icon). All these features reduce memory and information processing requirements on the inspector/mechanic. One other feature was a count of the time remaining to complete the workcard, shown by the slipping watch icon in Figs. 2 and 3. A typical task screen is shown as Fig. 3. A continuously updated Accountability List may also be viewed any time. As noted earlier, the Accountability List records the inspector/mechanic's activity using the workcard such as signoffs done, notes made, and tasks previewed. The system's outputs are the Accountability List and the Non-Routine Repairs the inspector/mechanic wrote up.

An inspector/mechanic accesses these features by selecting icons or radio buttons with pictures or

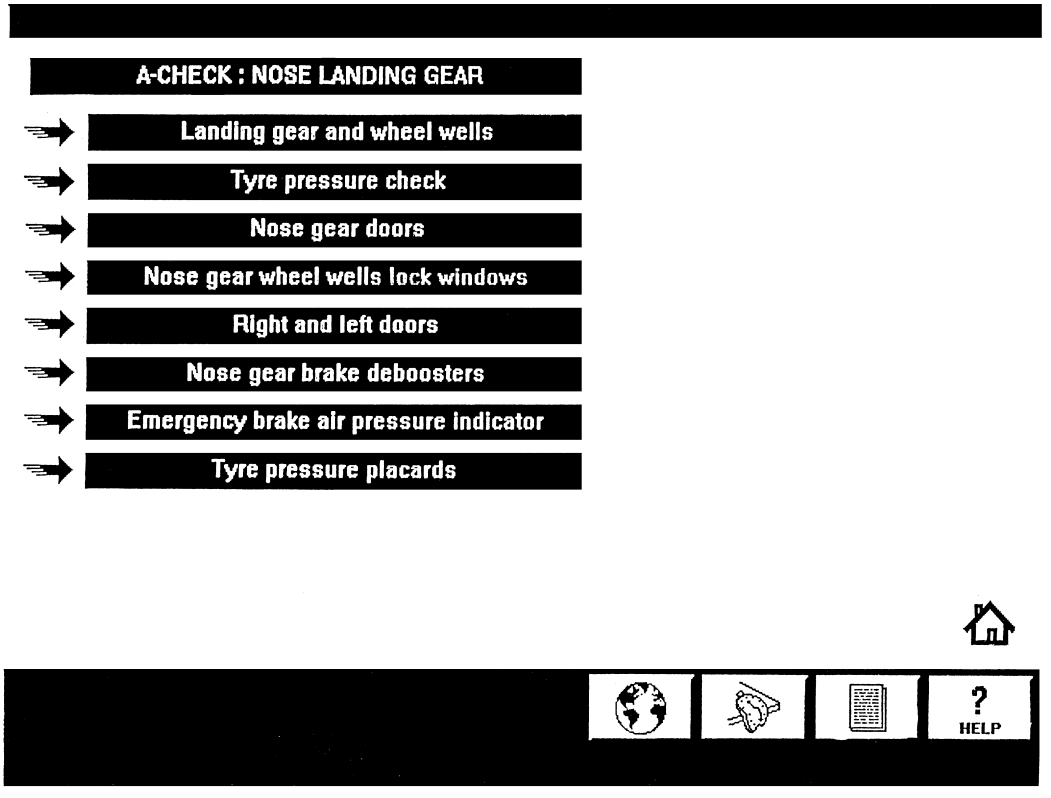

Fig. 2. Global view screen of computer-based workcard.

labels designed for rapid learning. Links between these features are explicit and always have a backtrack option (Vora and Helander, 1997) to counteract any tendency to become lost during navigation. Information for performing the tasks was categorized and layered to assist both experienced and inexperienced inspectors. General information was separated from specific task-directive information. All spatial information was conveyed through graphics. Thus, these features meet design requirements and address the issues for developing workcards for aircraft inspection and the guidelines for human–computer interfaces.

6. Evaluation of the workcards

6.1. Methodology

In the Patel et al. (1994) study, evaluation was by rating scale. Eight experienced inspectors used the original and improved workcards, rating each on fourteen 9-point scales. The current study used three versions of an A-check workcard. The computer-based workcard was compared against the current paper-based workcard and against the improved paper-based workcard designed by Patel et al. (1994). The comparison was made using questions derived from the issues identified by the taxonomies in Table 1 and in the earlier paper. The evaluation and the specific questions were designed to be similar to the evaluation of the C-check workcard performed by Patel et al. (1994).

All testing was confined by the airline to a single task and to a small number of inspectors. Thus, the inspectors had to perform each task three times on the different occasions, using one workcard each time. Such a design limitation meant that uncontrolled transfer effects between workcards would be possible (although not expected), so that this evaluation may not be as reliable as that performed by Patel et al. (1994). Eight inspectors, with the

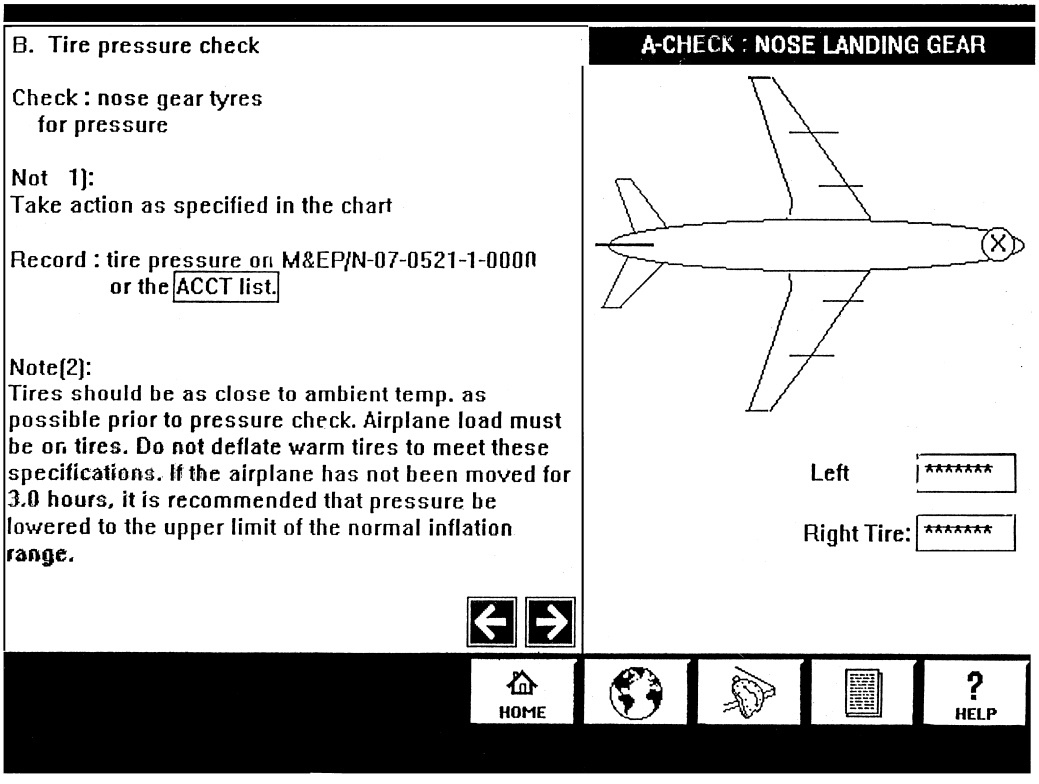

Fig. 3. Typical task screen of computer-based workcard.

demographic data shown in Table 2, used all three designs of the A-check workcards to perform a nose landing gear inspection with fifteen signoffs. The order of the three workcards was randomized across inspectors as complete counterbalancing was impossible with eight inspectors. They were given an overall briefing as to the purpose of the study and general instructions, and they answered a questionnaire on personal data. Before using the computer-based workcard, inspectors were given a training session. A quiz on using the computer-based workcard ensured that they understood how to use the computer functions of the workcard. After inspectors completed the inspection using each form of the workcard, they were asked to complete a questionnaire evaluating that workcard. The subjects rated their evaluation of the issues addressed by each question on a 9-point rating scale.

Table 2
Personal data on mechanics used to evaluate workcards

Characteristic	Mean	Standard deviation
Age (yr)	38.4	13.6
Years in civil aviation	9.9	8.8
Level of experience on A-checks (yr)	4.6	1.7
Average number of A-checks performed every month	3.8	4.1
Years of computer experience	3.5	1.9

7. Results and discussion

The demographic data on the inspectors (Table 2) values were reasonable for the inspector population, including a large variability in number

of A-checks they perform each month. We can compare the age and experience distributions to national statistics of the civil aviation maintenance workforce from the US Bureau of Labor Standards taken in 1977, which gave a mean age of 38.37 yr (SD = 10.92) and a mean experience of 12.87 yr (SD = 9.33). Our sample was not different in variability (Ages: $X^2(7) = 10.8$, $p > 0.10$; Experience: $X^2(7) = 6.2$, $p > 0.25$) or in mean (Age: $V = 0.01$, $p > 0.50$; Experience: $V = 0.84$, $p > 0.20$) from the national values. Note that the inspectors were not a random sample from the workforce, but rather all of the inspectors assigned to our study who agreed to take part.

Two analyses of the evaluation response data are of interest:

1. whether the features of the computer-based workcard were judged either better than or worse than a neutral rating,
2. how the computer-based workcard was evaluated in comparison with the existing paper-based workcard and the improved paper-based workcard.

For the first analysis, the median of the distribution of computer-based workcard scores on each scale was compared to the scale center point (score = 4) using a Wilcoxon one-sample test. A two-sided procedure was used, with $\alpha = 0.05$ as the criterion for significance. Note that only the scores from the computer-based workcard were used in this analysis. For the second analysis, a Friedman Two-way test was used for equality of the three median scores (original, improved, computer-based workcards). Non-parametric tests were chosen to avoid untested assumptions concerning normality and variance homogeneity with the rating scales used.

Results of the first analysis are presented in Table 3. The three parts of this table identify issues that were rated significantly better than neutral (A), not significantly different from neutral (B), and significantly worse than neutral (C). Of the 37 issues, 25 are were (A); 11, in (B); and 1, in (C), showing that inspectors were highly enthusiastic about most aspects of the system. Many items judged better than neutral were overall evaluations such as the degree to which workcards like these should be used, but some were for very specific features such as readability of buttons and icons, showing that both the overall concept and detailed design were rated highly. Most of the neutral responses (B) were for completeness and organization, or for features such as automatic generation of the Accountability List and Non-Routine Repair forms. Both of these activities (i.e. without the computer) are normally performed during quiet periods, such as break times, in the more comfortable surroundings of the inspectors ready room, thus giving inspectors a little more ready room time. Thus, the time savings, often seen by management as justification for such features, had in this instance social overtones. Inspectors clearly did not see these as a highly desirable feature of the computer-based workcard and remained neutral in their ratings. The only feature inspectors significantly disliked was one which showed what percentage of the standard time had been spent. As has been found consistently in our studies of airline maintenance, inspectors strenuously resist implications of time pressure in their jobs. They regard themselves as guardians of public safety and are vocal in defending against any perception of rushing (Drury and Lock, 1994; Patel et al., 1994). The time feature apparently created an impression of time pressure; it has now been removed.

The computer-based workcard compared favorably against both the current and proposed paper-based workcards. Table 4A and B show the mean ratings and standard deviations for the three workcards on each issue the computer- and the paper-based systems. As in Table 3, results have been divided into those where there was a significant difference among the three systems (Table 4A) and those where there was no difference (Table 4B). The inspectors did not rate the computer-based system worse than the paper-based system on any issue. Fourteen of the nineteen issues were rated significantly in favor of the computer-based system, including all issues asking for an overall evaluation of the system, and overall ease of usability of the workcard. The amount of information provided was judged almost the same in all three systems. This result was expected since no information was added to or subtracted from the original workcard to develop the two new systems.

Table 3
Classification of evaluation factors as better than, not different from, and worse than neutral rating using the Wilcoxon test[a]

$p < 0.01$	$p < 0.05$
A. *Significantly Better Than Neutral Rating*	
Readability of text	Task of reading
Readability of buttons and icons	Information covered everything for task
Readability of graphics	Separating information by frequency of use
Ease of understanding information	Flexibility of use
Ease of understanding symbols/icons	Ease of referring to attachments or manual
Higher chance of missing information	Often confused about location
Degree of interest	Often confused about how to return to previous location
Degree to which rater would like to use workcard again	Degree of fatigue after using the system
Degree to which workcards like these should be used	
Would rather rely on substituting computer for paper-based workcard	
Overall ease of usability	
Degree of simplicity	
Degree of tension while using system	
Usefulness of Global View feature	
Usefulness of Home View feature	
Usefulness of Automatic Non-Routine Writeup feature	
Usefulness of direct access to all references	
B. *Not Significantly Better than Neutral Rating*	
Tasks were well organized	
Effort required in locating information	
Consistency of organization	
Ease of physical use	
Ease of writing up an Accountability List	
Ease of writing up a Non-Routine	
Ease of learning to use the computer-based workcard	
Need to refer to "Global View"	
Performance rating using the computer-based workcard	
Usefulness of Automatic Accountability List Generation feature	
Usefulness of Writeup Note feature	
C. *Significantly Worse Than Neutral Rating*	
	Usefulness of Time Overview feature

[a]Note that for statements with a negativewording, a lower score means "better," so that the tests have been reversed for these statements.

From Table 5, much of the improvement between the original and computer-based workcards appears to be related to better layout, organization, and presentation of information, whether on hard-copy or on computer. The computer features added some benefit, but not much, to the improved paper-based workcard. One way to quantify this is shown in Fig. 4 where the "Overall Ease of Usability" ratings are given for the three workcards. The change from original to improved paper-based workcard (2.5 to 5.9) was 84% of the total change from original to computer-based workcard (2.5 to 6.5). This re-emphasizes the benefits of implementing good human factors principles in workcard design, whether or not the system is computerized. Practically, this means that improvements can be made to the current workcard system even without resorting to computer-based

Table 4
A. Issues which were significantly different using Friedman test

Issue addressed	9-Point ratingscale end points		Workcard system			Significance
	0	8	Current mean (SD)	Improved mean (SD)	Computer mean (SD)	
Ease of understanding	Very difficult	Very easy	4.4 (1.1)	6.25 (1.7)	7.1 (1.0)	0.02
Information covered everything for task	Disagree fully	Agree fully	1.5 (1.4)	4.4 (2.4)	6.6 (2.1)	0.01
Tasks were well organized	Disagree fully	Agree fully	1.9 (1.6)	5.5 (2.1)	6.1 (2.4)	0.02
Effort required in locating information	Very difficult	Very easy	1.8 (1.4)	5.5 (20.0)	5.8 (2.0)	0.01
Consistency of organization	Terrible	Excellent	3.4 (0.9)	5.3 (1.0)	5.4 (1.8)	0.05
Separating information by frequency of use	Terrible	Excellent	3.3 (1.6)	5.9 (1.4)	6.1 (1.6)	0.05
Chance of missing information	Always	Never	4.4 (0.7)	6.5 (1.7)	6.5 (0.9)	0.01
Ease of physical use	Very difficult	Very easy	3.0 (0.9)	5.5 (2.1)	6.4 (2.5)	0.05
Ease of referring to attachments or manual	Very difficult	Very easy	1.8 (1.7)	4.5 (2.3)	7.0 (1.9)	0.01
Ease of writing up an Accountability List	Very difficult	Very easy	2.4 (1.3)	4.8 (2.3)	5.1 (2.0)	0.05
Degree of interest	Very boring	Very interesting	2.3 (1.7)	4.8 (1.0)	6.9 (1.2)	0.01
Degree to which rater would like to use W/C again	Definitely not	Definitely yes	3.0 (1.1)	5.8 (1.3)	7.1 (0.9)	0.01
Degree to which W/C like these should be used	Definitely not	Definitely yes	3.1 (1.0)	5.9 (1.4)	6.3 (1.2)	0.01
Overall ease of usability of W/C	Terrible	Excellent	2.5 (0.9)	5.9 (1.4)	6.5 (1.4)	0.01

B. Issues which were non-Significantly different using Friedman test

Issue addressed	9-Point rating scale end points		Workcard system		
	0	8	Current	Improved	Computer
Readability of text	Terrible	Excellent	4.0 (2.1)	6.6 (1.4)	6.5 (0.76)
Task of reading	Very difficult	Very easy	3.9 (2.0)	6.5 (2.3)	6.6 (1.8)
Amount of information	Too little	Too much	4.8 (1.8)	4.0 (1.1)	3.5 (1.8)
Flexibility of use	Terrible	Excellent	3.5 (1.4)	5.5 (0.9)	5.6 (1.5)
Ease of writing up a Non-Routine	Very difficult	Very easy	2.9 (2.4)	4.9 (2.1)	5.4 (2.2)

systems. The text and graphics in our computer-based hypertext system were the same ones used in the improved paper-based system so that design effort on paper-based systems is not wasted when computer-based systems arrive.

All inspectors quickly became familiar with the computer-based system; no inspectors took more than one hour to learn the system well enough to go through the steps of single A-check task. More time would obviously be required for inspectors to become fully adept at navigating the system and using all of its features, but the time and cost overhead associated with introducing this system was very low. This vindicates the design philosophy which utilized detailed task analysis and human factors interpretation of the inspectors' jobs, and included feedback from the inspectors themselves, to produce the final design.

Hypertext interfaces can lead to problems of becoming lost during interface navigation. In this workcard implementation, the sequential nature of the tasks made it important to address this potential problem at the design stage. All links to back-up documents brought up a "back" button

Table 5
Pairwise comparisons among original paper-based, improved paper-based, and computer-based workcards, showing significance level on the Wilcoxon test

	9-point rating scale end-points		Significance of current paper-based Workcard versus		Significance of New Paper vs. Computer Workcard
Issue addressed	0	8	New Paper Workcard	Computer Workcard	
Readability of text	Terrible	Excellent	0.031	0.025	n.s.
Task of Reading	Very difficult	Very easy	n.s.	0.025	n.s.
Ease of understanding	Very difficult	Very easy	0.025	0.01	n.s.
Amount of information	Too little	Too much	n.s.	n.s.	n.s.
Information covered everything for task	Disagree fully	Agree fully	0.025	0.005	n.s.
Tasks were well organized	Disagree fully	Agree fully	0.031	0.005	n.s.
Effort required in locating information	Very difficult	Very easy	0.005	0.005	n.s.
Consistency of organization	Terrible	Excellent	0.025	0.025	n.s.
Separating information by frequency of use	Terrible	Excellent	0.025	0.025	n.s.
Chance of missing information	Always	Never	0.025	0.005	n.s.
Flexibility of use	Terrible	Excellent	0.031	n.s.	n.s.
Ease of physical use	Very difficult	Very easy	0.025	0.01	n.s.
Ease of referring to attachments or manual	Very difficult	Very easy	0.005	0.005	n.s.
Ease of writing up an Accountability List	Very difficult	Very easy	0.01	0.025	n.s.
Ease of writing up a Non-Routine	Very difficult	Very easy	0.025	n.s.	n.s.
Degree of interest	Very boring	Very interesting	0.01	0.005	0.025
Degree to which rater would like to use W/C again	Definitely not	Definitely yes	0.01	0.01	0.025
Degree to which W/C like these should be used	Definitely not	Definitely yes	0.01	0.025	n.s.
Overall ease of usability of W/C	Terrible	Excellent	0.025	0.005	n.s.

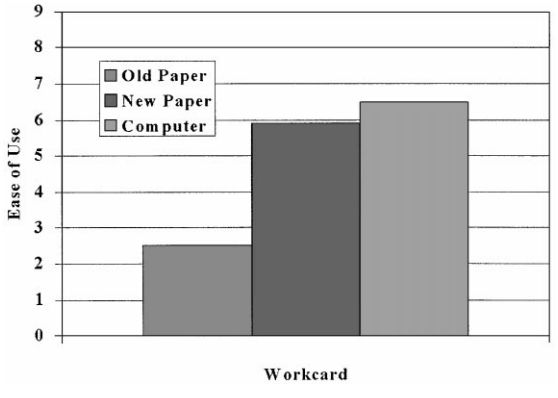

Fig. 4. Relative ease of use of the three workcard versions.

to return directly to the previous node. Inspectors would rarely need to link to nodes more than a single link distant from the main task, so that on most occasions only a single use of "back" would suffice, although multiple links *were* possible. Within the sequential task itself, the Accountability List kept track of which items had been completed and signed off, so that missing sign-offs were displayed wherever the Accountability List was accessed. Occasionally, tasks need to be performed out of order, for example to coordinate with other activities on the aircraft. We did not design the software to enforce a strict ordering to allow for this needed flexibility. In practice the ratings in Table 4A showed that the links were appreciated, with significant effects of "Ease of referring to attachments or manual" and "Effort required in locating information." Table 4B shows that "Flexibility of use" was not compromised. No inspector was seen to be lost in hypertext, and none asked for navigation assistence from the experimenters.

Despite the good rating of ease of physical use (Tables 3 and 4), the computer-based system can

clearly benefit from improved hardware. Weighing about 2.5 kg and requiring both a keyboard and a pointing device, the current system could not be used as easily as, for example, a future pen-based system.

Direct access to multiple layers of documentation, through hypertext, would be expected to reduce reliance on memory and to decrease waiting time to retrieve information compared to use of off-line manuals. Compared to the original paper-based workcard, the computer-based system was easier to understand, reduced the effort required to locate information, increased organization and consistency of information, and increased overall workcard usability. Most of the improvements from the computer-based system were also found for the improved paper-based system. It is important to make human factors improvements to existing workcard systems even before they are computerized.

8. Conclusions

A similar set of design guidelines to those used to improve paper-based workcards was developed and used to design a portable computer-based workcard system for A-checks and C-checks. An evaluation of this system against both the original and improved paper-based workcards for one task of an A-check showed that the computer-based system was better than either paper-based system. However, a major conclusion of the study was that much of the improvement over the original workcards could be obtained from redesign to incorporate human factors guidelines without leaving paper-based media. The inspectors found the computer-based workcards interesting and would like to see them implemented at the workplace. The time necessary to become familiar with the system was brief.

Acknowledgements

This work was performed under contract from the Federal Aviation Administration, Office of Aviation Medicine (Ms. Jean Watson) through Galaxy Scientific Corporation.

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